BINARIZATION OF PHASE CONTRAST VOLUME IMAGES OF FIBROUS MATERIALS: A CASE STUDY

Filip Malmberg
Centre for Image Analysis, Uppsala University, Uppsala, Sweden
filip@cb.uu.se

Catherine Östlund
STFI-Packforsk AB, Stockholm, Sweden
catherine.ostlund@stfi.se

Gunilla Borgefors
Centre for Image Analysis, Swedish University of Agriculture, Uppsala, Sweden
gunilla@cb.uu.se

Keywords: X-ray microtomography, Graph cut segmentation, Phase Contrast, Fibrous materials

Abstract: In this paper, we present a method for segmenting phase contrast volume images of fibrous materials into fibre and background. The method is based on graph cut segmentation, and is tested on high resolution X-ray microtomography volume images of wood fibres in paper an composites. The new method produces better results than a standard method based on edge-preserving smoothing and hysteresis thresholding. The most important improvement is that the proposed method handles thick and collapsed fibres more accurately than previous methods.

1 INTRODUCTION

1.1 Background

Wood fibres are used in many types of materials. The most common such materials are paper and board, which consist of a dense network of pulp fibres. Another, quite new application for wood fibres is composite materials, where a network of pulp fibres is used to reinforce a plastic matrix.

Recently, X-ray microtomography has been successfully used to capture high resolution volume images of fibrous materials non-destructively (Antoine et al., 2002; Samuelsen et al., 2001). Automated analysis of such images can give a lot of useful information about the properties of the material.

As described in (Samuelsen et al., 2001), the most straightforward way of providing the contrast necessary for imaging with X-rays is to use beam *absorption*. However, when imaging low-density materials, such as pulp fibres, it is difficult to get enough contrast using absorption. For such materials, *phase contrast* can be used instead. In phase contrast images, changes in refractive index of the imaged sample, i.e., the interfaces between different materials in the sample, are detected. In phase contrast volume images of fibrous materials, the interface between fibre and background is visible as a bright band on the fibre side of the interface and a dark band on the background side. These dark and bright bands will be denoted *interface bands*. A small part of a slice from a volume that exhibits these phenomena is shown in Figure 1.

Both absorption contrast and phase contrast effects may be present in an image. With X-ray microtomography, the balance between absorption contrast and phase contrast is determined by the distance between the sample and the imaging sensor.

Since many image analysis methods require a binary image as input, segmenting the images into fibre and background is an important pre-processing step. We call this step *binarization*. The balance between phase contrast and absorption contrast in the image affects the choice of binarization method.

In absorption images, the intensity of each image element corresponds to the density of the material it represents. Given that there are sufficient differences in density between the imaged materials, the intensity of an element directly indicates which material it belongs to. Thus the image can, in theory, be segmented by thresholding the intensity values. In practice, the image is often corrupted by noise and other artifacts, that must be removed or reduced before thresholding can be applied.

Phase contrast images are conceptually harder to binarize than absorption images, since most individual image elements contain no information about

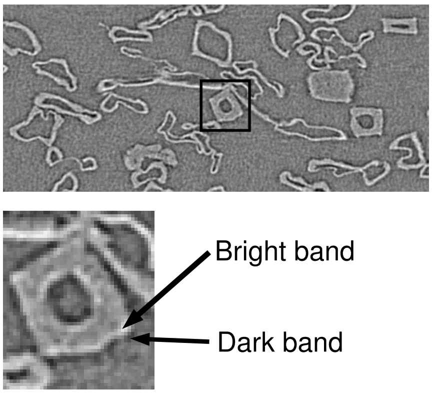


Figure 1: Part of a slice from a pulp-fibre composite sample imaged with phase contrast X-ray microtomography. Bright and dark interface bands are visible at the boundaries between fibre and background.

which material they belong to. Instead, we only have information about the boundaries between the different materials. At these boundaries, however, interface bands provide *local* information about which side of the boundary that corresponds to which material. To binarize the image, this local information must somehow be propagated to the rest of the image in a consistent way. Here, we present a method for binarizing phase contrast volume images containing two distinct materials. The method first identifies the interface bands using thresholding. These are then used as input for segmentation with *minimal graph cuts* (Boykov, 2006).

1.2 Previous Work

Binarization of absorption mode volume images of fibrous materials has been addressed in a number of papers during recent years. The most common approach is to use some kind of edge preserving smoothing to reduce image noise. The filtered image is then binarized using thresholding or region growing. Isolated structures that are considered too small to be fibres are then removed using morphological operations. Variants of this approach were used in, e.g., (du Roscoat et al., 2005), (Bache-Wiig and Henden, 2005) and (Martin-Herrero and Germain, 2007).

In the phase-contrast images shown here, the width of the interface bands are about the same as the width of the fibre walls. The interior of many fibres are therefore filled entirely by the bright interface band. This means that many fibres are brighter than the background. Therefore, it is tempting to use a threshold-based method for binarization. However, this approach will make it hard to correctly binarize collapsed fibres and fibres with thicker walls, since the interior of these fibres will have about the same intensity level as the background. Using edge-preserving filters, it may be possible to propagate the intensity values of the bright interface band to the interior of such fibres, although this might require very precise parameter settings and the results will be hard to predict.

A method for segmenting phase contrast images of carbon-carbon composites is presented in (Vignoles, 2001). Two thresholds, one high and one low, are applied to the image to identify the bright and dark interface bands respectively. An intermediate image is then constructed where the identified bright interface bands are set to white, the identified dark interface bands are set to black, and all other image elements are set to gray. We will call this type of intermediate image a *trimap*.

Two different methods for reconstructing the segmented image from the trimap are described in (Vignoles, 2001). In the first method, the boundary of each connected gray region is examined. If the boundary is predominantly white, the region is labeled as white, and vice versa. This method is based on the assumption that there are no holes in the interface bands. This assumption is often violated in real images, due to noise and other artifacts, and in such cases the method may fail drastically.

In the second method, all gray elements that have at least one non-gray neighbor are examined. If the element has more white neighbors than black neighbors, it is set to white. Else it is set to black. This procedure is repeated until no gray elements remain. This method is more robust to "leaks" in the bands than the first method. However, only the binary information from the identified interface bands is used to delineate the boundaries in the image. In regions where the interface bands are too weak to be correctly identified by thresholding, no image information is used in the delineation of the fibre boundary.

1.3 Outline of the Proposed Method

The method proposed in this paper is conceptually similar to the methods in (Vignoles, 2001). Just as in that paper, a trimap, where each element is labeled as either fibre, background or unknown, is created. We will, however, use minimal graph cuts to create a binary image from the trimap. Segmentation with graph cuts will be explained in detail in the next section. Using graph cuts has the advantage that image information can be taken into account even in areas where the interface bands are too weak to be detected by thresholding.

2 Graph Cut Segmentation

Graph cut segmentation is an image segmentation method based on combinatorial optimization techniques. The method is applicable to images of any dimension and gives a binary partitioning of the image into background and object.

In graph cut segmentation the image is interpreted as a graph, where image elements correspond to nodes and paths between adjacent elements correspond to graph edges. Each graph edge is assigned a non-negative cost. Two special nodes are added to the graph, the *source* node and the *sink* node. Image elements that are a priori known to belong to the object are connected to the source node with zero cost edges. Similarly, elements that are known to belong to the background are connected to the sink node. A *cut* on the a graph is a set of edges that, if removed from the graph, separate the source from the sink. A cut thus associates each node with either the source or the sink. The *cost* of a cut is the sum of the cost of all edges in the cut, and a *minimal cut* is a cut such that no other cut has a lower cost. A computationally efficient algorithm for computing minimal graph cuts was described in (Boykov and Kolmogorov, 2004).

The fundamental idea of graph cut segmentation is that a minimal cut on the graph of an image corresponds to an optimal partitioning of the image into background and object, subject to the constraints given by the edge weights and the geometry of the graph. An illustration of this concept is shown in Figure 2.

From a user perspective, this means that we must supply a *trimap* image, where each element is labeled as either *background*, *object* or *unknown*. Furthermore we must supply a *costmap* image, where the value of each element is inversely proportional to the "likelihood" that the element belongs to the boundary of the object of interest. This is typically based on image features that describe strong edges in the image, such as the gradient magnitude of the image. The graph cut method then produces a binary segmentation, where the boundary between the object and the background is located at strong edges in the image.

3 Method

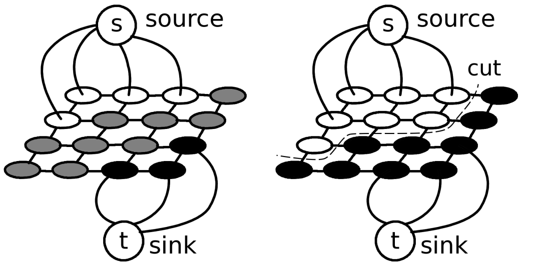


Figure 2: Principle of graph cut segmentation. Left: Initial state of the graph. Right: A cut on the graph.

In order to apply graph cut segmentation to phase contrast images, we need to create a trimap and a costmap. The trimap is created using essentially the same approach as that in (Vignoles, 2001). The volume is thresholded at two values, one low value and one high value. This produces two binary images that represent the dark and bright interface bands, respectively.

For images with strong noise, good threshold values may not exist. In such cases we have used hysteresis thresholding (Canny, 1986) to identify the interface bands. The user must thus specify two threshold values, $t_{1,1}$ and $t_{1,2}$, for segmenting the bright interface bands, and two threshold values, $t_{2,1}$ and $t_{2,2}$, for segmenting the dark interface bands.

The two binary images containing the interface bands are then merged into a single trimap. The trimap does not have to be complete, i.e., leaks in the interface bands are allowed. However, elements wrongly labeled as fibre or background should be avoided, since any such errors will remain in the final binarization.

Since the graph cut algorithm is computationally expensive, it is desirable to keep the number of nodes in the graph as small as possible. In practice, only the unknown elements are included in the graph. Reducing the number of unknown elements in the trimap thus reduces the computation time.

In order to exclude uninteresting elements (i.e. elements that are highly unlikely to belong to a fibre) from the computations we have used the following heuristic: A 3D distance transform (Borgefors, 1996) is computed from the bright image elements, i.e. elements known to be inside the fibres. The distance map is truncated at some distance value, and elements with larger distance values are labeled as background. The threshold value should be as small as possible in order to minimize the computation time, but still large enough not to discard any fibre elements. We have found during our experiments that suitable values for a batch of images are not hard to find manually by visual inspection.

The costmap c is computed using 3D Sobel filters.

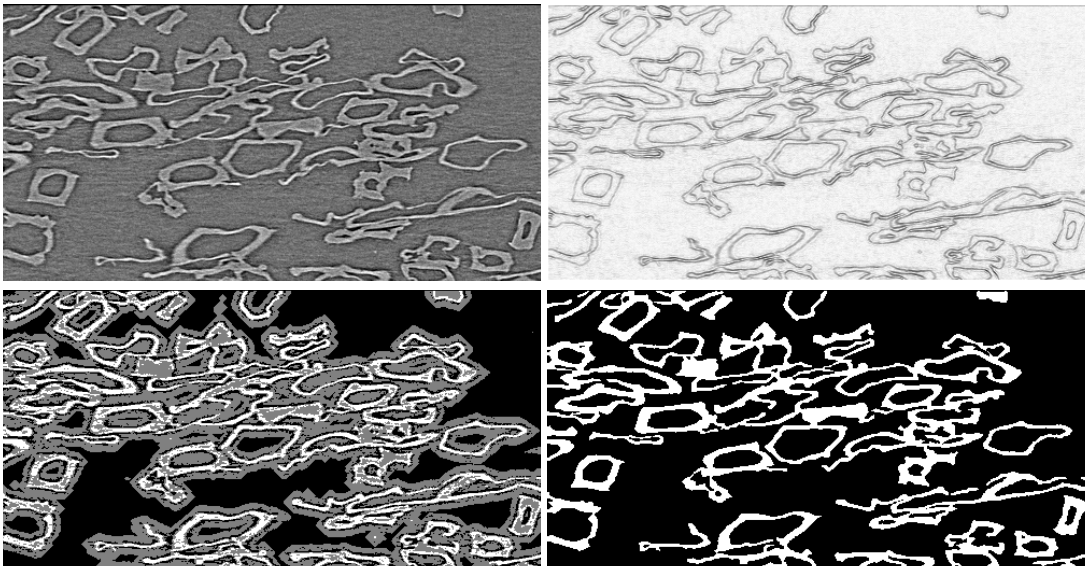


Figure 3: The different steps of the proposed method. Top left: A slice from the original volume. Top right: Costmap. Bottom left: Trimap. Bottom right: Binarization result after graph cut segmentation and removal of small isolated structures.

Edge responses dx, dy and dz are computed separately along the three coordinate axes of the volume. The following convolution filter is used in each direction:

$$\begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix}$$

The magnitude of the gradient vector formed by these three components is then used as a cost function:

$$c = \sqrt{dx^2 + dy^2 + dz^2} \qquad (1)$$

Once the trimap and the costmap are created, graphcut segmentation is applied.

If the trimap contains some false fibre regions due to noise in the image, this might result in small isolated fibre regions in the binarized image. As an optional post-processing step, isolated regions smaller than some specified size (e.g., a few elements) may be removed using morphological operations (Sonka et al., 1998). The different steps of the method are shown in Figure 3.

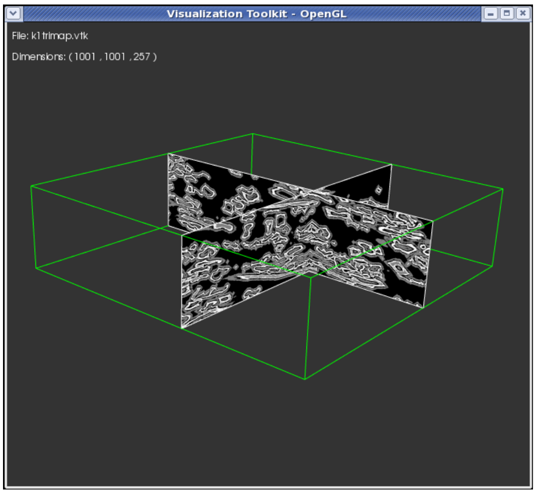
4 Experiments

Volume images of fibrous materials (paper, board, pulp-fibre composites) were captured with X-ray microtomography at the European Synchrotron Radiation Facility (ESRF) in Grenoble, at the ID19 beam line. The size of each reconstructed volume is 2048x2048x1280 voxels, with gray-values in the range [0,255]. The voxels are isotropic, with a side length of approximately 0.7 µm. Ring artifacts present in the images were reduced using the method described in (Axelsson et al., 2006).

The volumes were binarized using the proposed method. In order to reduce computation time, each volume was divided into subvolumes (512x512x256), and graph cut segmentation was applied separately to each of the subvolumes. This procedure might possibly introduce some errors at the borders of the subvolumes. However, we were unable to detect any such errors during visual inspection of the merged results.

Parameters for the construction of the trimaps were determined through visual inspection, and the same parameters were used for all subvolumes. A software tool for quick visual inspection of volume images, developed using *The Visualization Toolkit* (VTK) (The Visualization Toolkit, 2008), was used to make the evaluation easier. A screenshot from this tool is shown in Figure 4. Table 1 shows the parameter settings for two different materials, a pulp-fibre composite and a newsprint paper.

For comparison purposes, the volumes were also binarized using a threshold-based method. Following the method described in (Bache-Wiig and Henden, 2005), image noise was first reduced using iterated SUSAN-filtering (Smith and Brady, 1997). The filtered volumes were then binarized using hysteresis thresholding.



File: k1trimap.vtk

Dimensions: (1001 , 1001 , 257)

Figure 4: A screenshot from a tool, developed using VTK, for quick visual inspection of volume images. The tool was used to facilitate evaluation of parameter settings.

Table 1: Examples of parameter settings for trimap construction.

Sample	$t_{1,1}$	$t_{1,2}$	$t_{2,1}$	$t_{2,2}$
Pulp-fibre composite	190	170	80	80
Newsprint paper	185	165	80	80

5 Results

No ground truth segmentation exists for the studied volumes, and therefore it is difficult to make a quantitative comparison between the two tested methods. Visual inspection of many segmented images, however, reveals some systematic differences. Both methods produce good segmentation results for thin, hollow fibres. For collapsed and thick fibres, however, the threshold based method often fails to fill the interior of the fibre. As discussed in section 1.2, this is due the fact that the SUSAN-filtering fails to propagate intensity values from the boundary of the fibre far enough into the interior regions. The proposed graph cut based method, on the other hand, handles these cases correctly. An example of this is shown in Figure 6. Surface renderings of two samples, binarized using the proposed method, are shown in Figure 5.

The computation time for the proposed method is dominated by the graph cut segmentation. For each subvolume, the graph cut segmentation was computed in 3-4 minutes on a computer with eight 3GHz Intel processors and 32 GB of RAM.

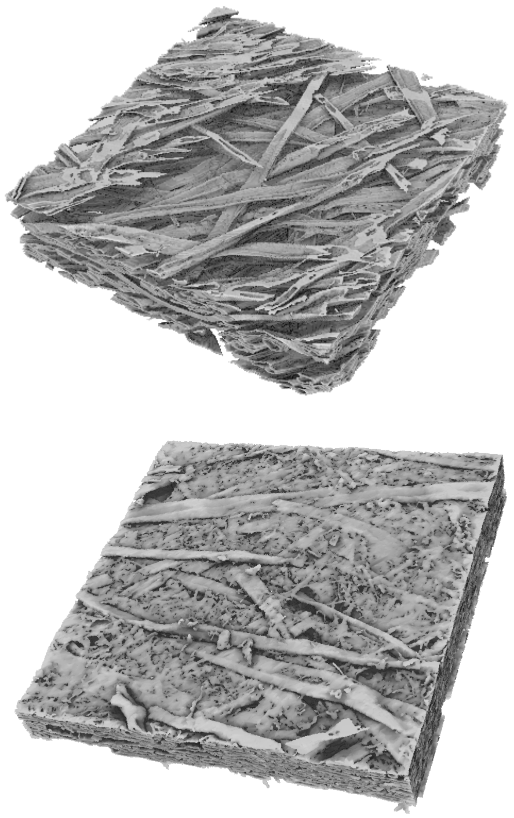


Figure 5: Surface renderings of two samples, binarized using the proposed method. Top: Pulp-fibre composite. Bottom: Newsprint paper.

6 Conclusions

For X-ray microtomography images where the phase contrast is stronger than the absorption contrast, the proposed method gives better results than previous methods based on the combination of edge-preserving smoothing and thresholding.

The method might also be applied to other phase contrast images. For the method to work, the images should contain no more than two separate materials. The refractive indices of the materials must be sufficiently different, so that the interface bands at the boundary between the materials can be identified with thresholding.

Acknowledgment

The European Synchrotron Radiation Facility (ESRF) in Grenoble is gratefully acknowledged for the 3D image data acquired during the Long Term project ME-704, that was used in this study.

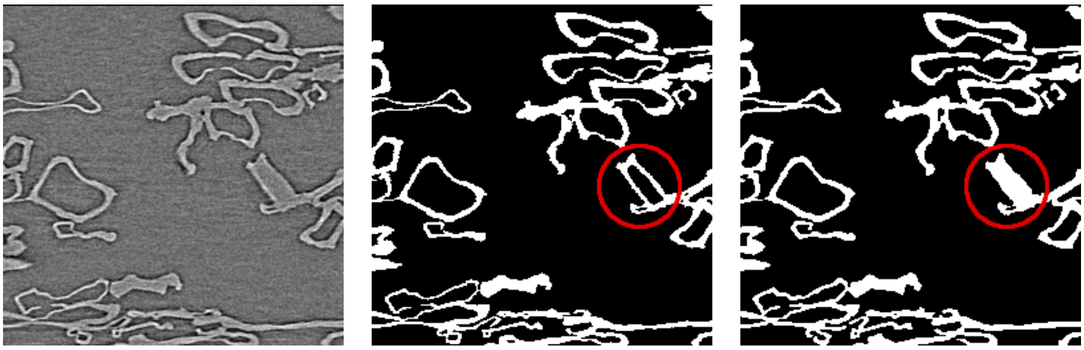


Figure 6: Comparison between threshold-based binarization and the proposed method. The red circles indicate a typical example of a collapsed fibre where the threshold-based method fails. Left: Original slice. Middle: The same slice, binarized with iterated SUSAN-filtering and hysteresis thresholding. Right: The same slice, binarized with the proposed method.

REFERENCES

Antoine, C., Nygård, P., Gregersen, Ø. W., Holmstad, R., Weitkamp, T., and Rau, C. (2002). 3d images of paper obtained by phase-contrast x-ray microtomography: image quality and binarization. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 490(1-2):392 –402.

Axelsson, M., Svensson, S., and Borgefors, G. (2006). Reduction of ring artifacts in high resolution X-ray microtomography images. In et al., F., editor, *Proceedings of DAGM*, volume LNCS 4174, pages 61–70.

Bache-Wiig, J. and Henden, P. (2005). Individual fiber segmentation of three dimensional microtomograms of paper and fiber-reinforced composite materials. Master's thesis, Norwegian University of Science and Technology. Available at `http://www.pvv.org/~perchrh/papers/`, accessed 8 September 2008.

Borgefors, G. (1996). On digital distance transforms in three dimensions. *Computer Vision and Image Understanding*, 64(3):368 – 76.

Boykov, Y. (2006). Graph cuts and efficient n-d image segmentation. *International Journal of Computer Vision*, 70(2):109–131.

Boykov, Y. and Kolmogorov, V. (2004). An experimental comparison of min-cut/max-flow algorithms for energy minimization in vision. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 26(9):1124–1137.

Canny, J. F. (1986). A computational approach to edge detection. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 8(6):679–698.

du Roscoat, S. R., Bloch, J., and Thibault, X. (2005). Synchrotron radiation microtomography applied to investigation of paper. *Journal of Physics D: Applied Physics*, 38(10A):78–84.

Martin-Herrero, J. and Germain, C. (2007). Microstructure reconstruction of fibrous C/C composites from x-ray microtomography. *Carbon*, 45(6):1242 – 53.

Samuelsen, E., Gregersen, O., Houen, P., Helle, T., Raven, C., and Snigirev, A. (2001). Three-dimensional imaging of paper by use of synchrotron x-ray microtomography. *Journal of Pulp and Paper Science*, 27(2):50–53.

Smith, S. and Brady, J. (1997). SUSAN- a new approach to low level image processing. *Int. Journal of Computer Vision*, 23(1):45–78.

Sonka, M., Havlac, V., and Boyle, R. (1998). *Image Processing, Analysis, and Machine Vision*. International Thomson Publishing Company, second edition.

The Visualization Toolkit (2008). `http://www.vtk.org`. Accessed 8 September 2008.

Vignoles, G. (2001). Image segmentation for phase-contrast hard x-ray CMT of C/C composites. *Carbon*, 39(2):167 – 73.